Measurement of sin 2β from $B \rightarrow J/\psi\ K_S$ Decays

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For CDF Collaboration

- Theory
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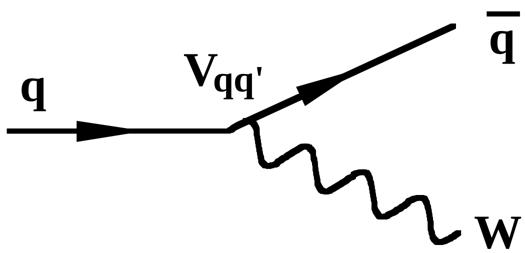
- CDF Detector
- $J/\psi\ K_S$ Events
- Flavor Tagging
- Results
- Prospects for Run II

CKM Matrix

Coupling between up-like quark q and down-like quark q' is proportional to $V_{qq'}$



$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

V is unitary and is parameterized by 3 angles and a phase.
A nonzero phase gives CP violation.

Wolfenstein Parameterization

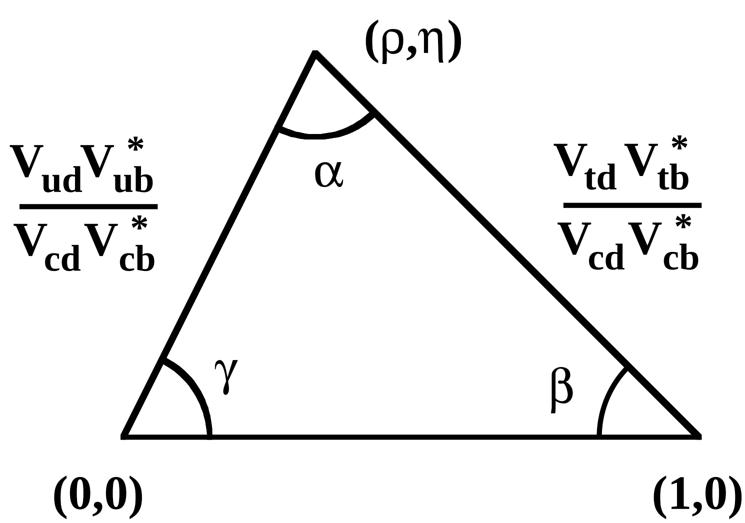
$$\mathbf{V} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$\lambda = \sin\theta_c$ **(sine of Cabibbo angle)**

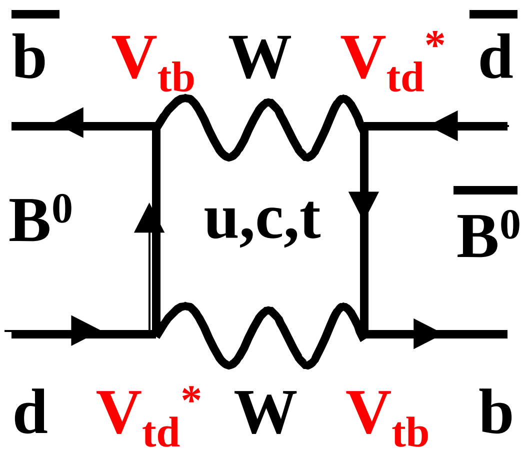
$V^\dagger V = V V^\dagger = I$

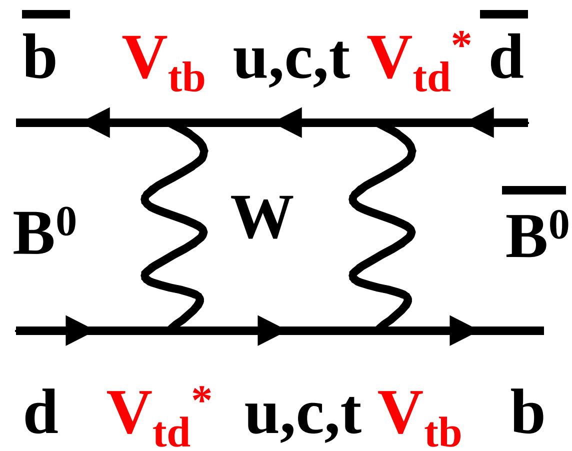
This gives relationships like

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$



$B^0\,\overline{B^0}$ Mixing





$$\sim V_{tb}^2\, V_{td}^{*2} = |\, V_{tb}\, V_{td}\, |^2\, e^{-2i\beta}$$

The $B^0\,\overline{B^0}$ mix to form mass eigenstates (B_L and B_H).

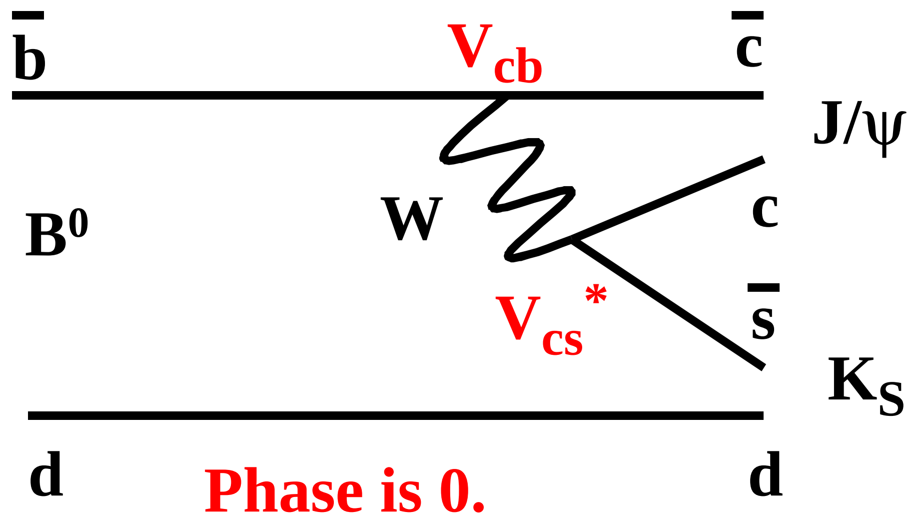
$\Delta m_d = m_H - m_L = 0.464 \pm 0.018\ \text{ps}^{-1}$

$\Gamma = 0.641 \pm 0.016\ \text{ps}^{-1}$

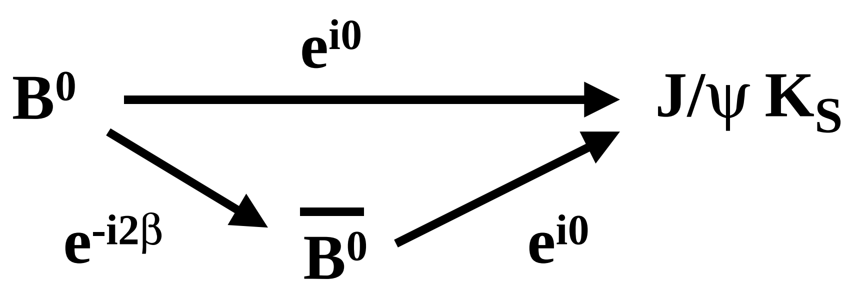
$\Delta\Gamma = \Gamma_H - \Gamma_L\ (\approx 0)$

$$P(B^0 \to \overline{B}^0) = \tfrac{1}{2}\Gamma e^{-\Gamma t}\left(1 - \cos \Delta m_d t\right)$$

$B \to J/\psi\ K_S$



CP violation comes from interference of two amplitudes.



CP Asymmetry

$$\frac{dN\left(\overline{B}^0 \to J/\psi K_S\right)}{dt} \propto e^{-\Gamma t}\left(1+\sin 2\beta \sin \Delta m_d t\right)$$

$$\frac{dN\left(B^0 \to J/\psi K_S\right)}{dt} \propto e^{-\Gamma t}\left(1-\sin 2\beta \sin \Delta m_d t\right)$$

The CP asymmetry is

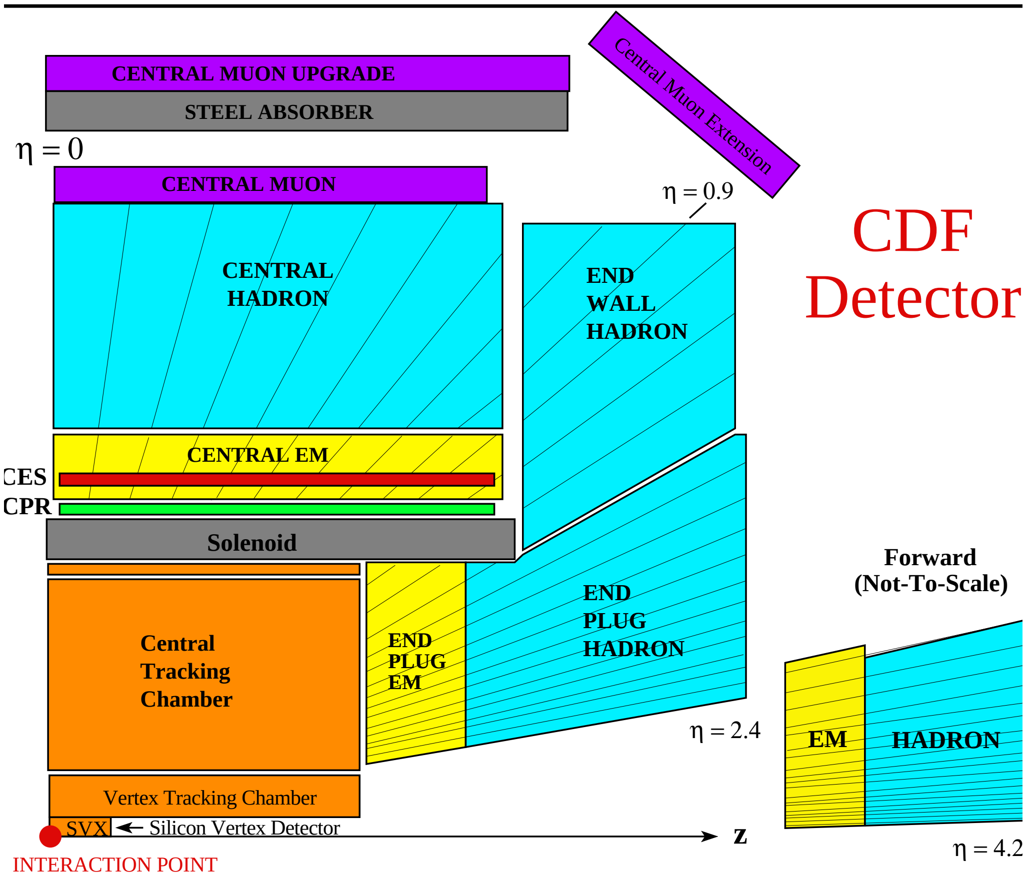
$$A(t) \equiv \frac{\frac{dN_{\overline{B}}}{dt} - \frac{dN_B}{dt}}{\frac{dN_{\overline{B}}}{dt} + \frac{dN_B}{dt}} = \sin 2\beta \sin \Delta m_d t$$

The time-integrated CP asymmetry is

$$\overline{A} = \frac{\int \frac{dN_{\overline{B}}}{dt} dt - \int \frac{dN_B}{dt} dt}{\int \frac{dN_{\overline{B}}}{dt} dt + \int \frac{dN_B}{dt} dt} = \sin 2\beta \frac{\Delta m_d \Gamma}{\Delta m_d^2 + \Gamma^2}$$

Previous Measurements

- **Opal (January, 1998)**
  D. Ackerstaff, *et al.*, Euro. Phys. Jour. C5, 379 (1998)
  - ➤ $\sin 2\beta = 3.2^{+1.8}_{-2.0}$ **(stat) ± 0.5 (syst)**
  - ➤ **from ~ 14 B $\rightarrow$ J/ψ K_S decays**
- **CDF (June, 1998)**
  F. Abe, *et al.*, PRL 81, 5513 (1998)
  - ➤ $\sin 2\beta = 1.8 \pm 1.1$ **(stat) ± 0.5 (syst)**
  - ➤ **from 200 B $\rightarrow$ J/ψ K_S decays with precise lifetime information, but only one flavor tagging method.**
  - ➤ **included in this measurement**
- **Indirect (from sin θ_C, Δm_d, Δm_s, and ε_K)**
  S. Mele, CERN-EP-98-133 (1998)
  - ➤ $\sin 2\beta = 0.75 \pm 0.09$

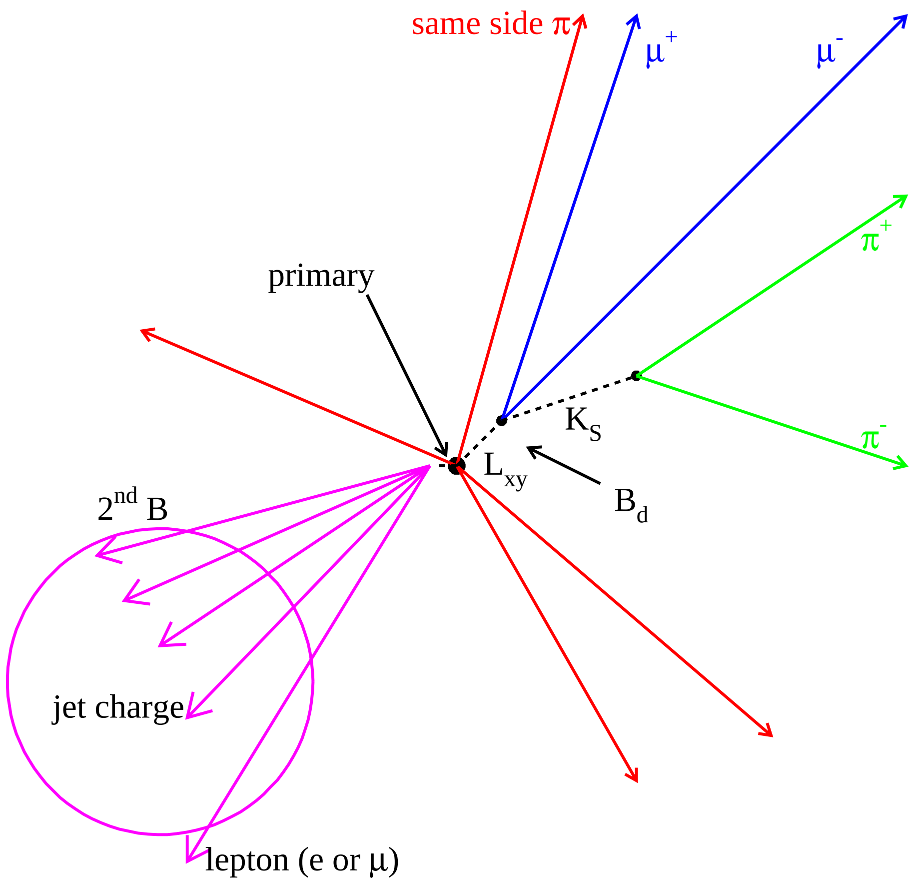


110 pb^{-1} of $\bar{p}p$ data at $\sqrt{s}$ = 1.8 TeV at Fermilab Tevatron

Important Aspects:

- **Silicon vertex detector -**
  Typical 2d vertex error is 60μm
- **Central tracking chamber -**
  Typical $J/\psi\ K_S$ mass resolution is 10 MeV/c^2
- **Muon systems and calorimeters -**
  Triggering and lepton identification

Analysis Overview



- **SST: same-side charged hadron tag**
- **SLT: opposite-side soft *e* or *μ* tag**
- **JETQ: opposite-side jet charge tag**

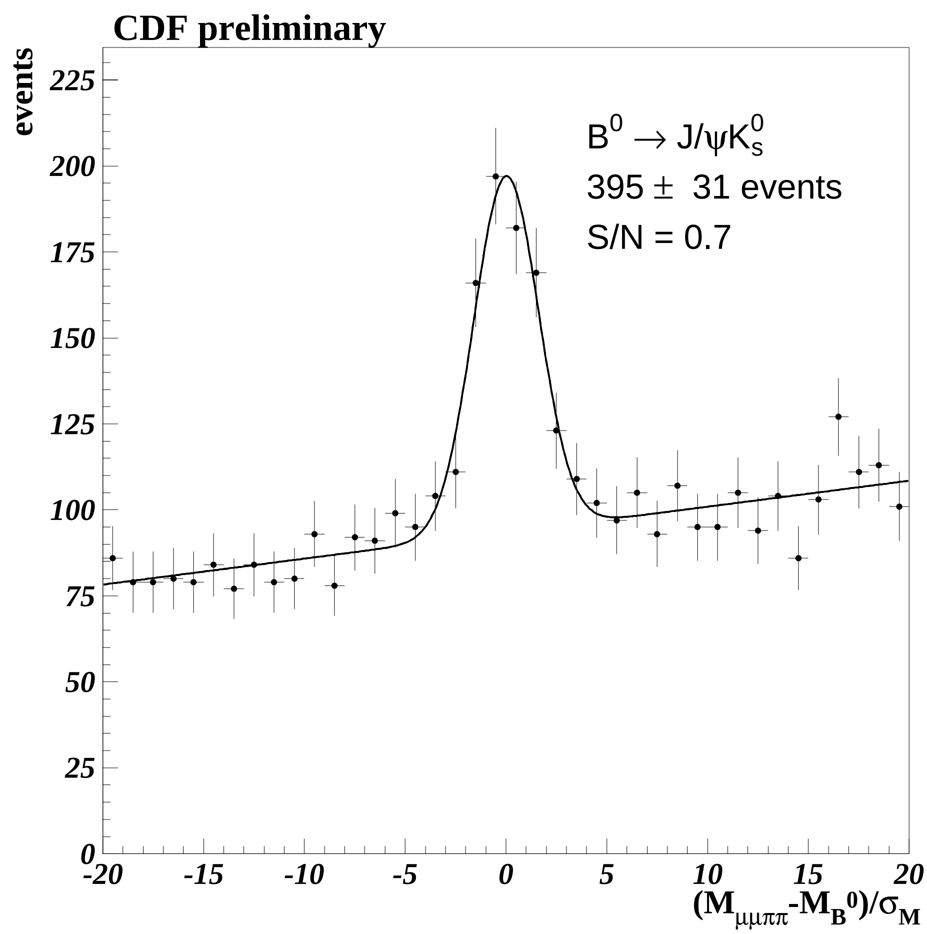
Event Selection

❶ $J/\psi \to \mu^+\mu^-$
2 opposite sign central tracks + matching muon chamber track

❷ $K_S \to \pi^+\pi^-$
2 opposite sign central tracks with a displaced vertex ($L_{xy} > 5\sigma$).

❸ **Fit the 4 tracks to $B \to J/\psi\ K_S$.**
- $\pi^+\pi^-$ **constrained to K_S mass.**
- K_S **vertex points to B vertex.**
- $\mu^+\mu^-$ **constrained to J/ψ mass.**
- **B vertex points to primary vertex.**
- **Require good fit quality.**

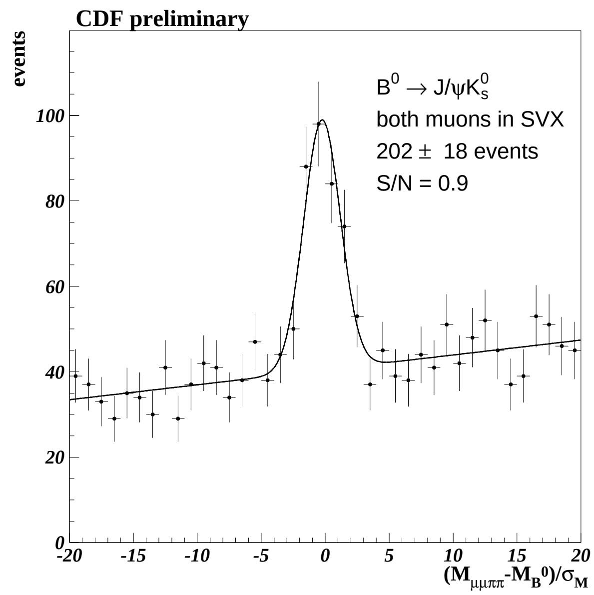
Event Yield



- 395 ± 31 events
- Most background is at small decay lengths
- "Normalized" mass is $\dfrac{m^{fit}_{\mu\mu\pi\pi} - M_{B^0}}{\sigma_m}$
- σ_m ~ 10-15 MeV/c^2

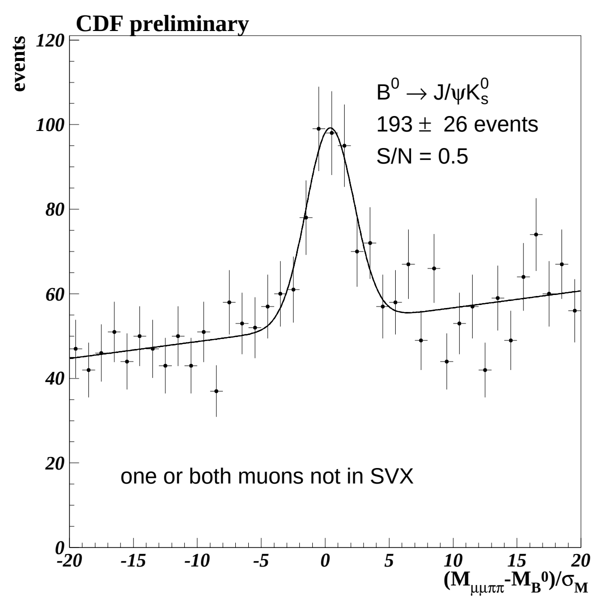
About 200 events have both muons in the silicon vertex detector

$\Rightarrow$ precise lifetime information



About 200 events have one or both muons not in the silicon vertex detector

$\Rightarrow$ imprecise lifetime information



Explanation of εD^2

Let A be an asymmetry given by

$$A = \frac{N_+ - N_-}{N_+ + N_-}$$

Suppose the measured asymmetry is
A_m = DA (D is known as the dilution).
The error on A is

$$\sigma_A = \frac{\sqrt{1 - D^2A^2}}{\sqrt{D^2 N_{tag}}} = \frac{\sqrt{1 - D^2A^2}}{\sqrt{\varepsilon D^2 N}} \xrightarrow[A \text{ or } D \ll 1]{} \frac{1}{\sqrt{\varepsilon D^2 N}}$$

εD^2 gives the statistical power, that is, N real events are equivalent to $\varepsilon D^2 N$ perfect events.

For example,

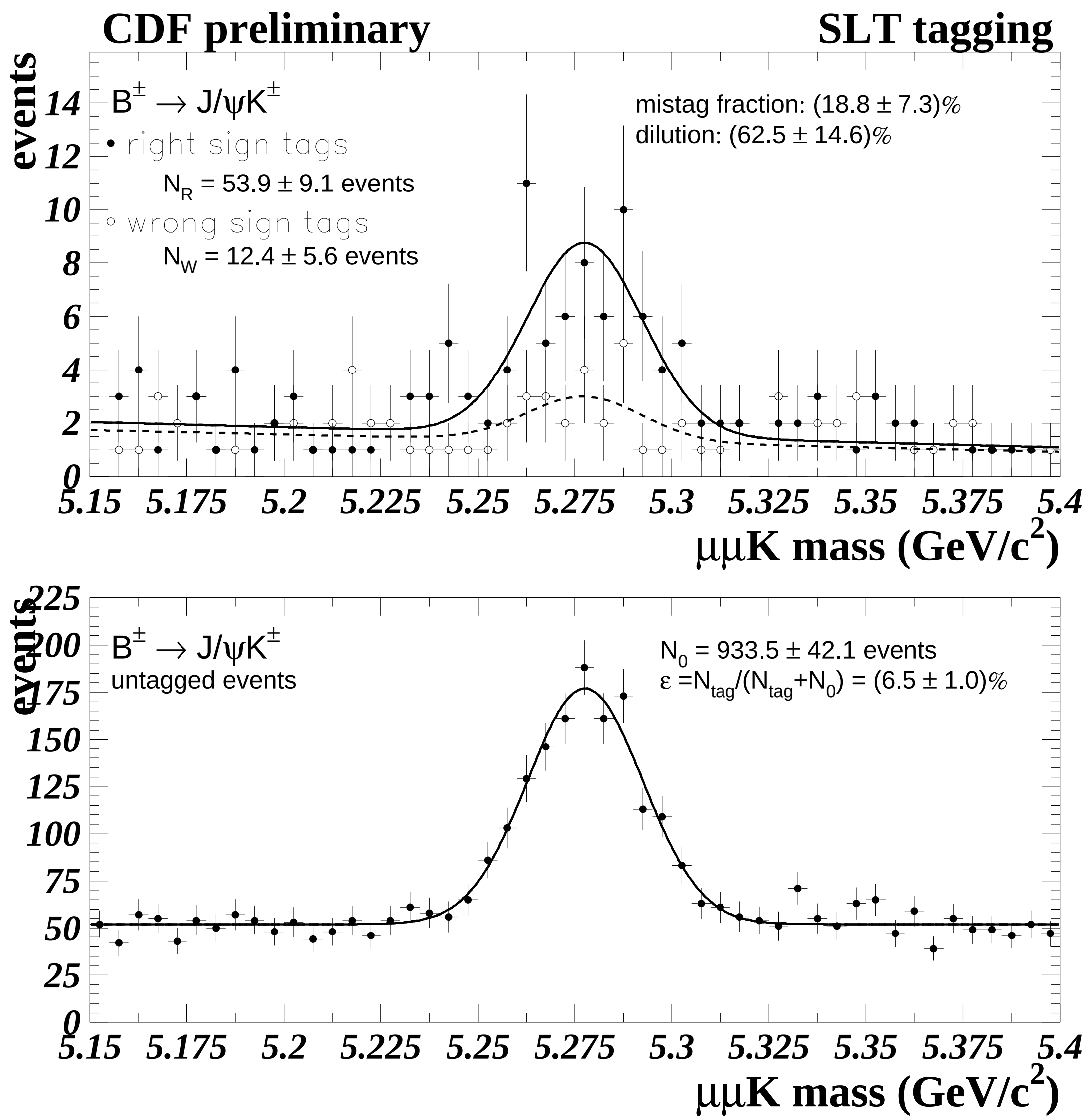
❶ **if background fraction is f_{BG}, D_{BG} = 1- f_{BG}**

❷ **if mistag probability is f, D_{mistag} = 1- 2f**

Soft Lepton Tag

- Look for semileptonic B decay opposite to $J/\psi\ K_S$
- Electron: central track that matches cluster in electromagnetic calorimeter ($P_T > 1$ GeV/c)
- Muons: central track matched to stub in muon chambers ($P_T > 2$ GeV/c)
- Use $B^{\pm} \rightarrow J/\psi\ K^{\pm}$ events to calibrate

Calibration of SLT Tag



$D = 0.625 \pm 0.146$

$\varepsilon = 6.5 \pm 1.0\%$

$\varepsilon D^2 = 2.2 \pm 1.0\%$

Jet Charge Tag

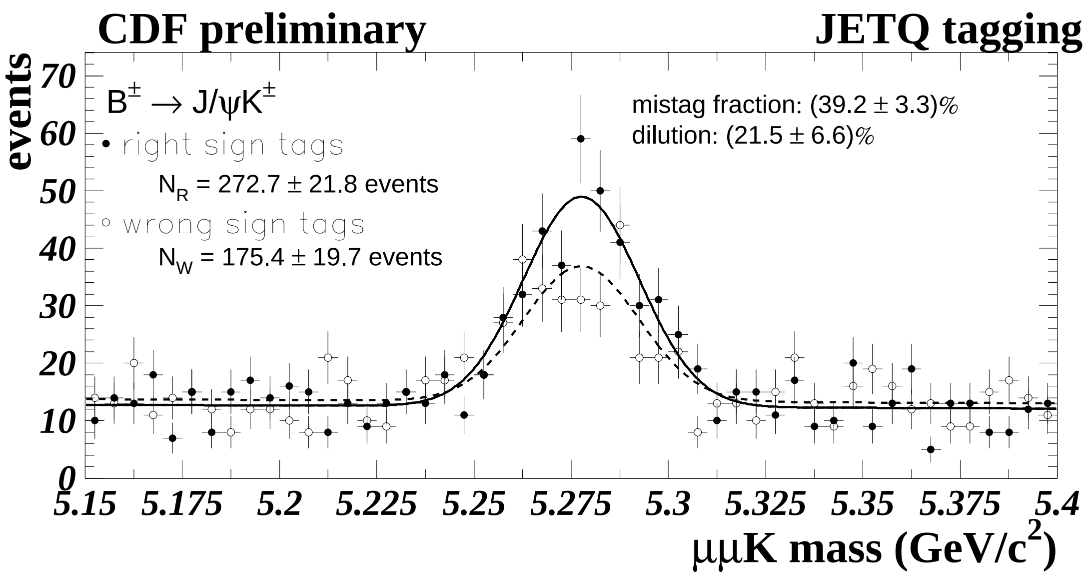
- Identify opposite side B by B jet
  (b $\rightarrow$ B + jet)
- Tracks are clustered using an invariant mass algorithm (cutoff of 5 GeV/c^2)
- Sum charges weighted by P_T and impact parameter

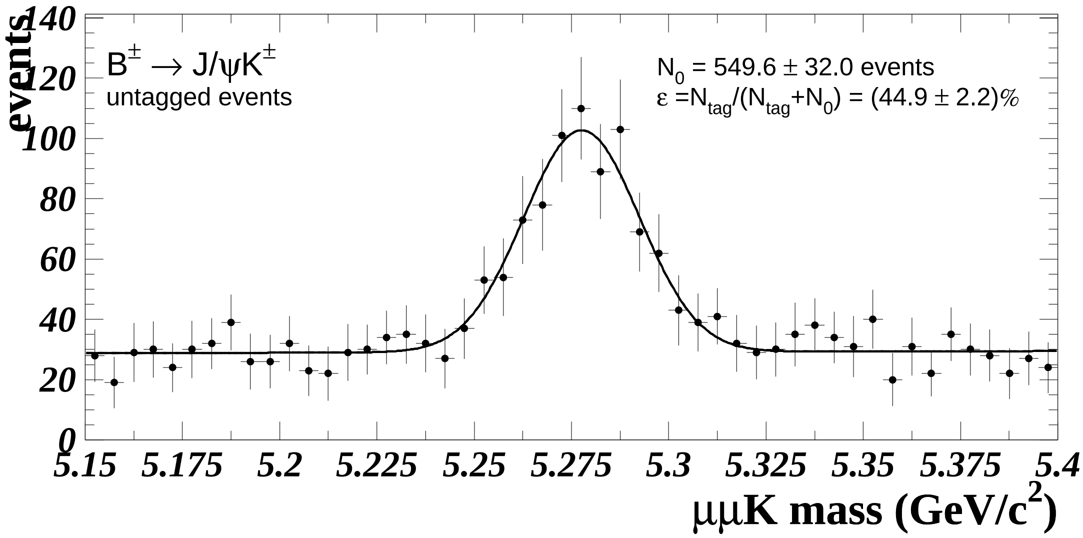
$$Q_{jet} = \frac{\sum_{tracks} q_i P_{Ti}\left(2 - T_i\right)}{\sum_{tracks} P_{Ti}\left(2 - T_i\right)}$$

where T is the probability the track came from the primary vertex (small for B daughters)

- $-1 \leq Q_{jet} \leq 1$
  $Q_{jet} > 0.20 \Rightarrow \bar{B} \rightarrow J/\psi\, K_S$
  $Q_{jet} < -0.20 \Rightarrow B \rightarrow J/\psi\, K_S$
  $|\, Q_{jet} \,| < 0.20 \Rightarrow$ no tag
- Use $B^{\pm} \rightarrow J/\psi\, K^{\pm}$ events to calibrate

Calibration of JETQ Tag





$D = 0.215 \pm 0.066$

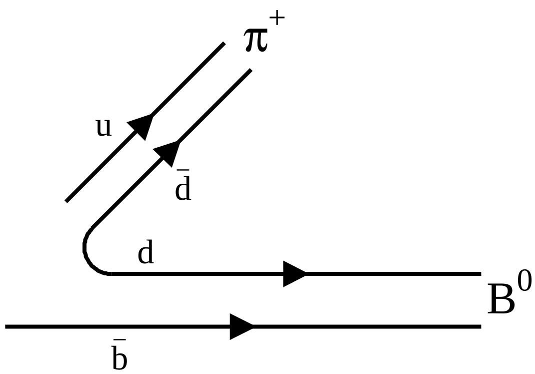
$\varepsilon = 44.9 \pm 2.2\%$

$\varepsilon D^2 = 2.2 \pm 1.3\%$

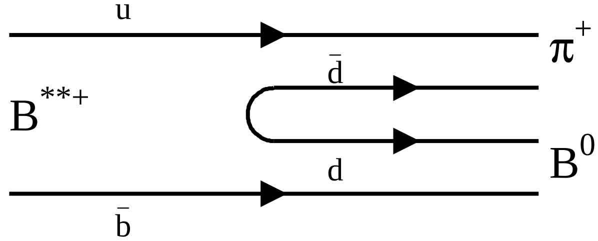
Same Side Tag

- The charge of hadrons near B's are correlated with the type of B at production due to

Fragmentation **Excited States**



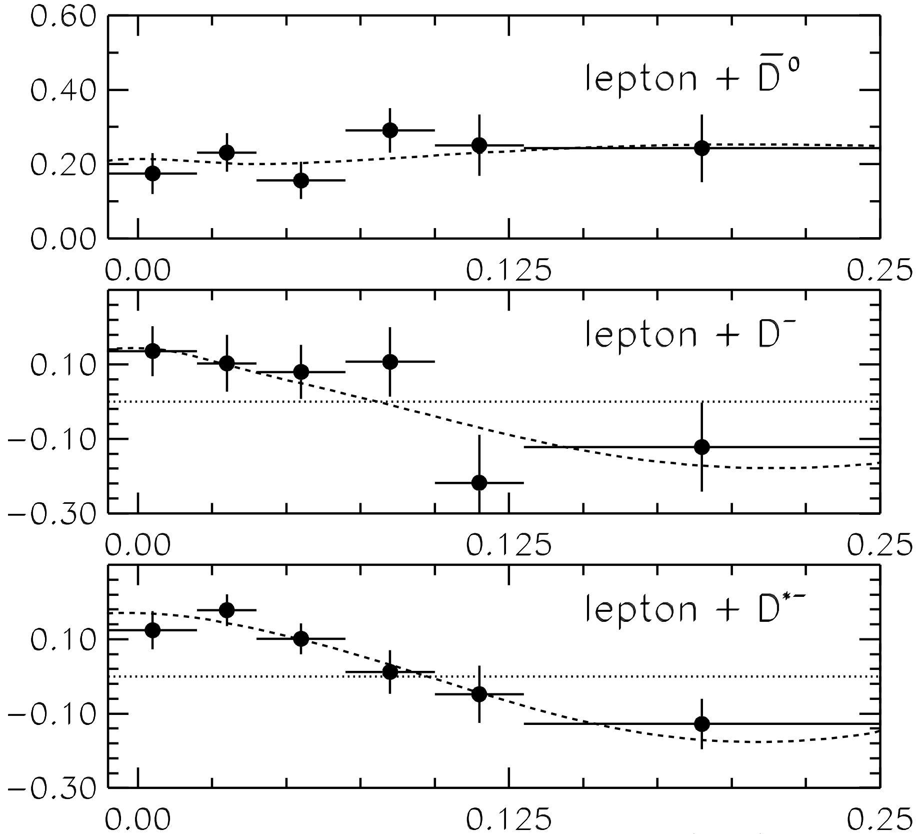
fragmentation



via B^{**}

- If more than one charged hadron is close to the B, the one with the lowest transverse momentum to the B is used.
- Use lepton-D events to calibrate

Calibration of SST Tag



$B^+ \rightarrow l^+ D^0$
3000 events

$B^0 \rightarrow l^+ D^-$
2000 events

$B^0 \rightarrow l^+ D^{*-}$
4300 events

$B^\pm$: $D_\pm = 0.27 \pm 0.03$ (stat) $\pm\ 0.02$ (syst)

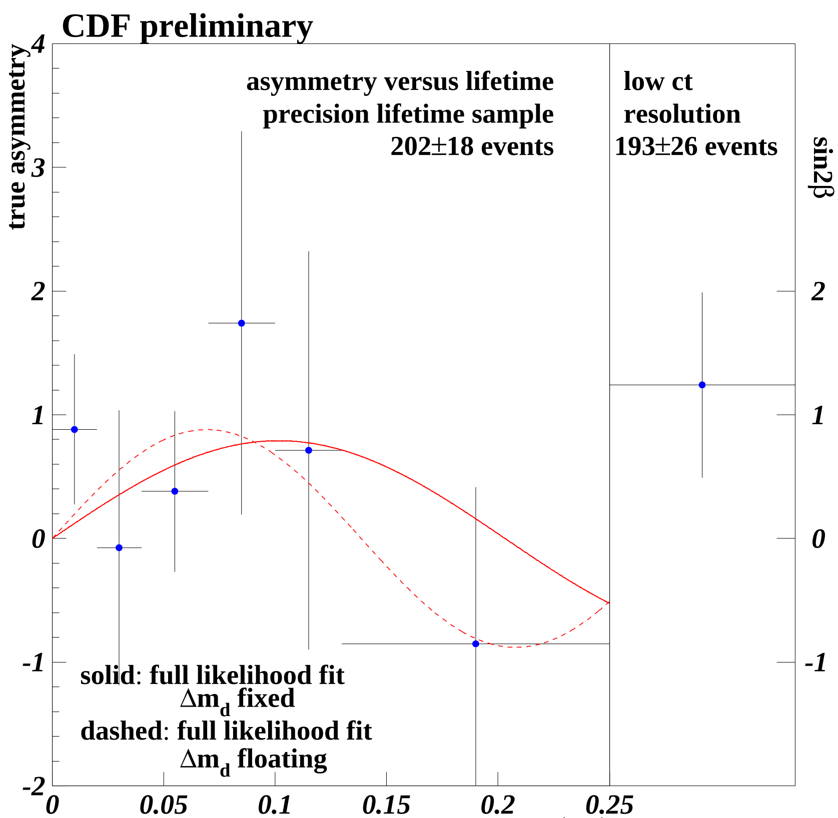
B^0: $D_0 = 0.18 \pm 0.03$ (stat) $\pm\ 0.02$ (syst)
$\varepsilon = 65 \pm 1.0\%$

$\varepsilon D^2 = 2.1 \pm 0.5\%$

Results

An unbinned maximum likelihood fit is done to the signal, prompt background, and long-lived background, including terms for lifetime, mass, and tagging efficiency.

$$\sin 2\beta = 0.79 \, {}^{+0.41}_{-0.44} \ (\text{stat.} + \text{syst.})$$



Systematic Errors

Separating the statistical and systematic errors gives

$$\sin 2\beta = 0.79 \pm 0.39\ (\mathrm{stat}) \pm 0.16\ (\mathrm{syst})$$

Summary of systematic errors:

Parameter	$\delta \sin 2\beta$
Tagging dilution	0.16
Tagging efficiency	
Δm_d	0.01
τ_{B^0}	0.01
m_B	0.01
Trigger bias	negligible
K_L regeneration	negligible

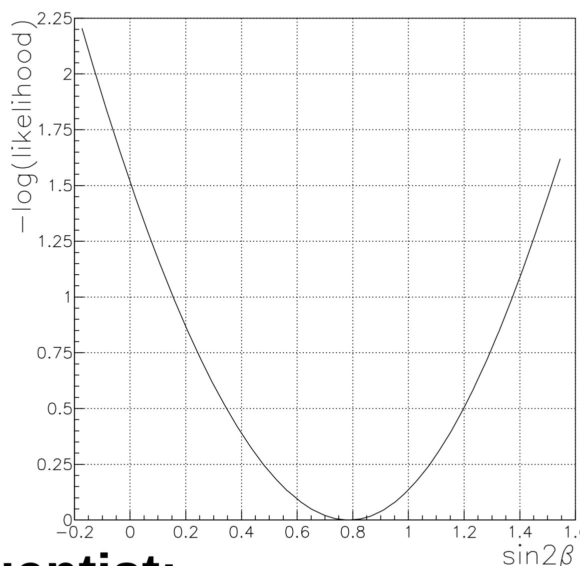
Limits

We measure:

$$\sin 2\beta = 0.79 \,{}^{+0.41}_{-0.44}\, (\text{stat.} + \text{syst.})$$

(Note: this result is with Δm_d constrained to the world average.)

A scan of the likelihood function:



Feldman-Cousins frequentist:

- $0 < \sin 2\beta < 1$ **at** 93% CL

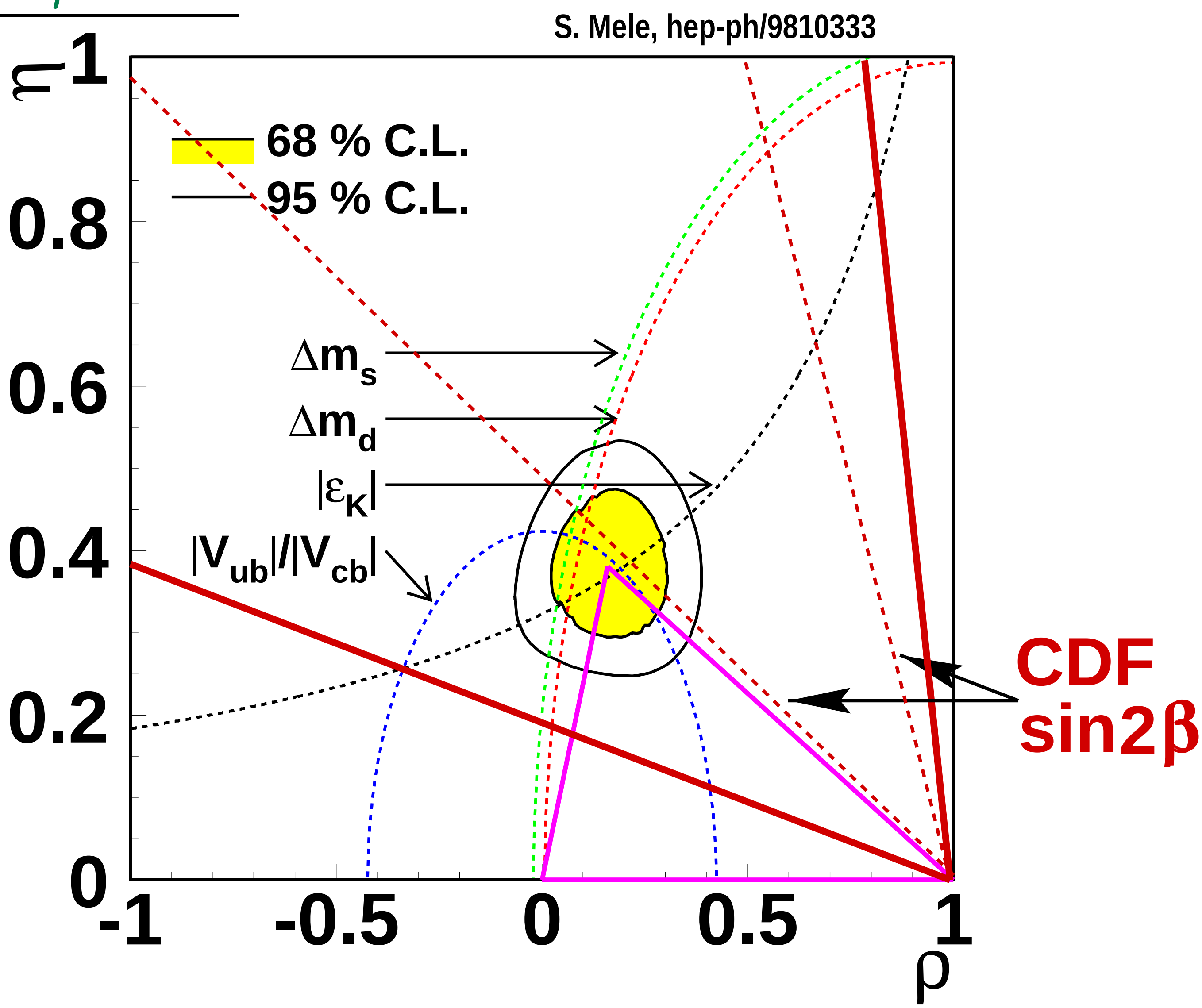
Bayesian (assuming flat prior in $\sin 2\beta$)

- $0 < \sin 2\beta < 1$ **at** 95% CL

Assume $\sin 2\beta = 0$
integrate Gaussian from $0.79 \to \infty$:

- **Prob($\sin 2\beta > 0.79$) =** 3.6%

ρ-η Plane



In going from $\sin 2\beta \Rightarrow \beta$ pick up a fourfold ambiguity:

- two solutions for $\rho < 1$, $\eta > 0$ (shown)
- two solutions for $\rho > 1$, $\eta < 0$ (not shown)

The solid red lines are the 1σ bounds, which account for the two possible values for β in the region $\eta > 0$.

Future Measurement of sin 2β

Run II to start in early 2001

- x20 integrated luminosity (20 fb^{-1})
- Increased vertex detector coverage
- 25% improvement in muon and trigger efficiency

We expect ~10,000 B^0 $J/\psi\ K_S$ events

$\Rightarrow \delta \sin 2\beta \leq 0.08$

In addition, we plan to

- Add $J/\psi \rightarrow e^+ e^-$
- Further increase muon coverage
- Improve flavor tagging (e.g., time-of-flight)

Conclusions

From 110 pb^{-1} of $\bar{p}p$ data at $\sqrt{s} = 1.8$ TeV,
CDF has isolated about 400 B^0 J/ψ K_S decays.

Using 3 flavor tagging methods and a maximum likelihood fit, we have determined

$$\sin 2\beta = 0.79 \,^{+0.041}_{-0.044} \text{ (stat+syst)}$$

$$0 < \sin 2\beta < 1 \qquad \text{at 93\% CL}$$

In Run II, we expect to measure sin 2β to a precision of at least 0.08.